YENSEN

A Study of Iron Alloys

Electrical Engineering

M. S.

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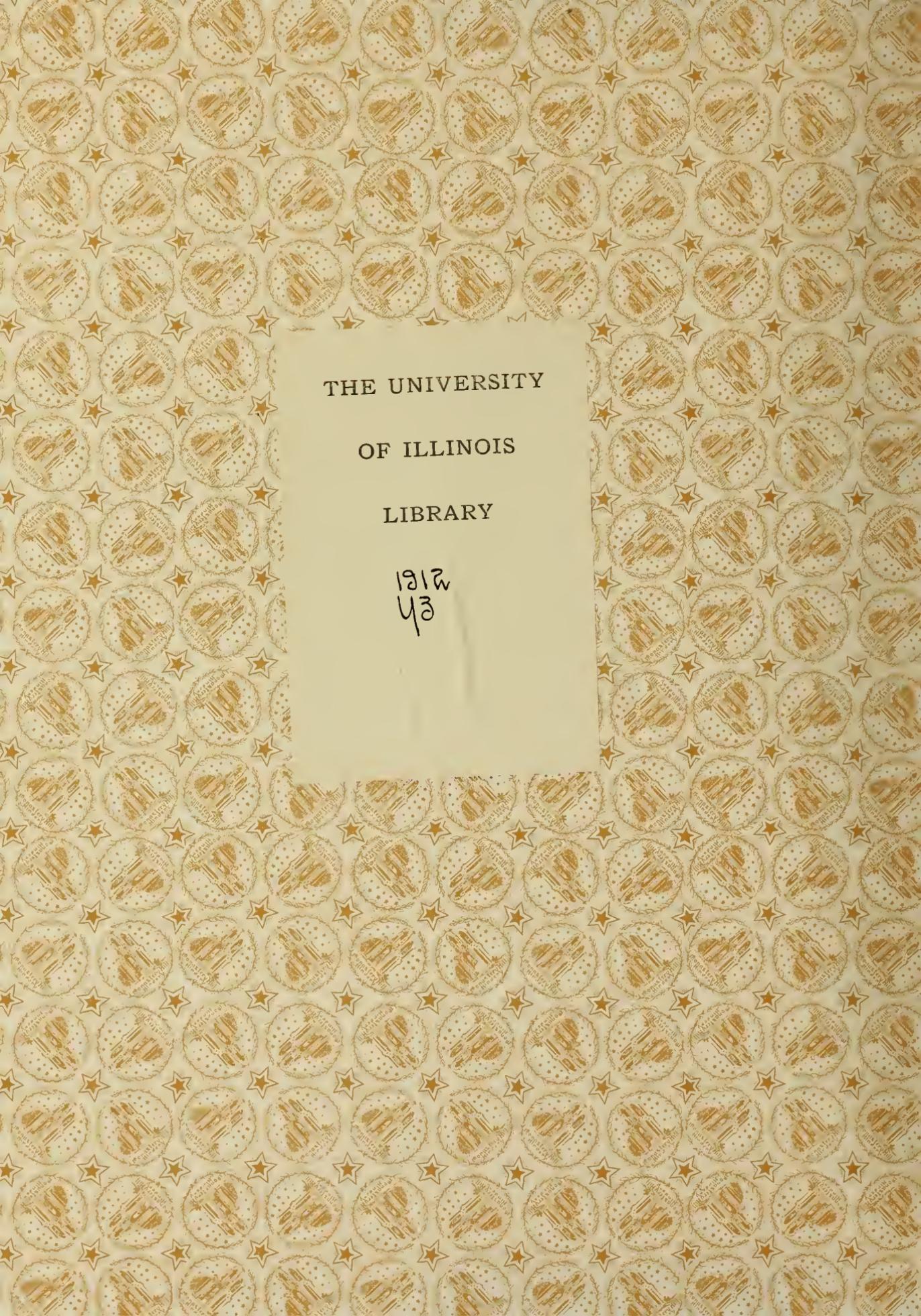
A STUDY OF IRON ALLOYS

BY

TRYGVE D. YENSEN

B. S., University of Illinois, 1907

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN ELECTRICAL ENGINEERING

IN

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May 31, 1912

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

TRYGVE D. YENSEN

ENTITLED   A STUDY OF IRON ALLOYS

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF   MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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--- CONTENTS ---

A STUDY OF IRON ALLOYS
I INTORDUCTION

1.   Scope.   Conservation of natural resources in one of the great problems of modern times, and the problem of economy in the use of materials is one of the most important in this connection. The experiments recorded in this thesis were undertaken with the view to improve the economy in the use of materials for electromagnetic machinery by increasing the magnetic permeability of the iron.

The experiments treat the effect upon the magnetic qualities of nearly chemically pure iron by adding to it an oxide of Boron. This oxide is commercially known as Boron Suboxide and has an approximate composition B_7O.   It was originally intended to take up various heat treatments of the alloys as well as a certain amount of metallography, but on account of seriousdelays in receiving the apparatus needed, the thesis is limited to a comparison of the permeability of the alloys,firstly as forged and secondly after annealing at 900° C. The permeability thus obtained must not be taken as a final value, as it is well known that further annealing has a marked beneficial effect upon permeability. It is also believed that the iron has been very slightly oxidized in melting--a point which will be taken up later--and this would naturally have a disadvantageous effect upon the permeability. However, the results may be looked upon as an indication of what may be expected of the final product after proper treatment.

As a confirmation of the permeability tests the tensile strength, together with the elongation and reduction

of area was measured for most of the alloys, as it is generally accepted that ductility and high permeability go together.

Finally in order to get an indication of the eddy current losses the electrical resistance of the alloys was measured.

2.   Historical Review.

On account of the relatively small importance attached to the magnetic qualities of iron previous to the appearance of electrical machinery, it is only comparatively recently that serious efforts have been made to improve these qualities, and the published literature upon the subject is rather scant.

Two very important researches have been published during the last ten years, and will be reviewed briefly.

(1)   Barrett, Brown, and Hadfield: "Researches on different alloys of iron", Journal of the Institution of Electrical Engineers, Vol. 31, page 674, February 13, 1902. The electrical and magnetic qualities are recorded of some 100 alloys of iron with carbon, manganese, nickel, tungsten, aluminium, silicon, cromium and copper. Swedish charcoal iron of a purity of 98.97 per cent iron was used as a basis.

As to the electrical resistance the results show that: the increase in specific resistance by adding 1% of one of the above metals is about proportional to the specific heat of the alloying metal, or inversely proportional to its atomic weight. Fig. 1 shows the permeability of the various alloys for H = 8 c.g.s. units. Fig. 2 gives the saturation curves for Swedish charcoal iron and the 2 1/4% aluminium and the 2 1/2% silicon

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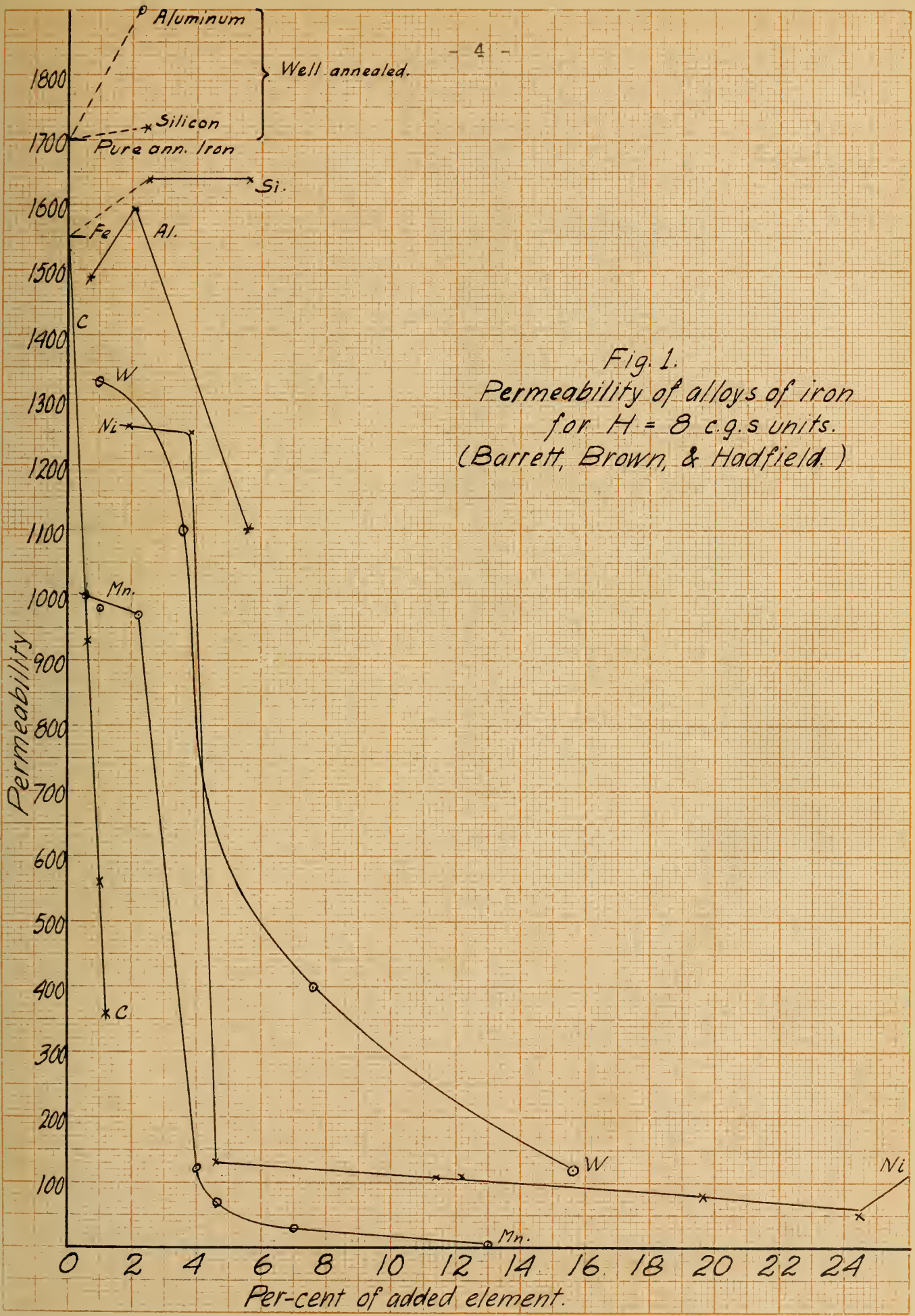
Fig. 1.
Permeability of alloys of iron
for H = 8 c.g.s units.
(Barrett, Brown, & Hadfield.)

$B \times 10^3$

2¼% Aluminum.

2½% Silicon
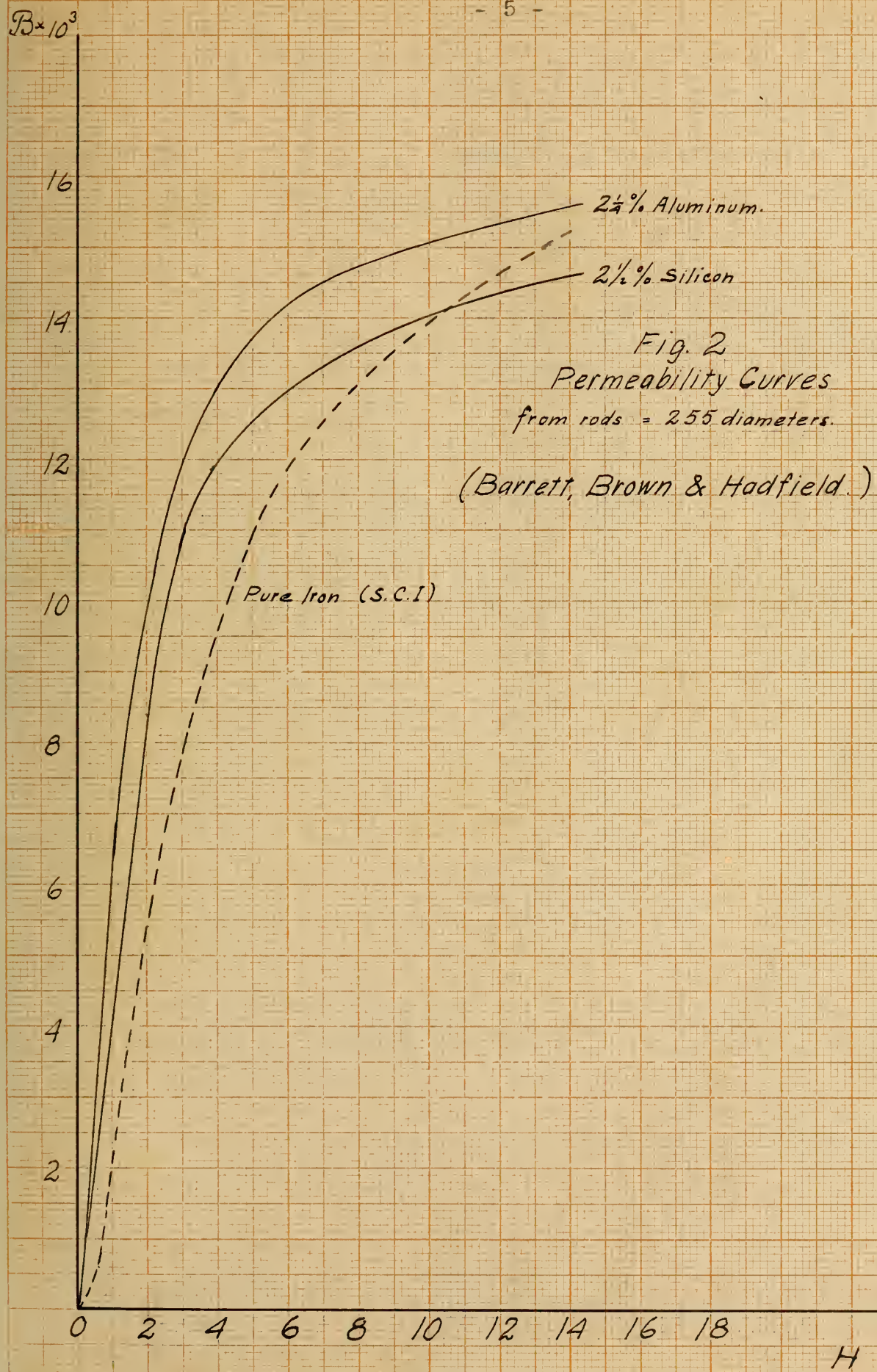
Fig. 2
Permeability Curves
from rods = 255 diameters.

(Barrett, Brown & Hadfield.)

Pure Iron (S.C.I)

H

TABLE I

Hysteresis Loss

(Barrett, Brown & Hadfield)

Specimen	Hyst. Const.	Hysteresis Loss (Watts per cu. inch)	
		Max. Ind.=5000	Max. Ind.= 9000
S. C. I. (Sw. Charcoal Iron)	.0011	.149	.382
Soft. Com. Iron	.002	.272	.695
S.C.I. with $2\frac{1}{2}$ % Si.	.00073	.123	.254
" " $2\frac{1}{4}$ % Al.	.00068		.236

Alloys. Table 1 gives the hysteresis loss for these same alloys. It is seen that out of the eight metals investigated only Silicon and aluminium have a beneficial effect upon the magnetic qualities of the iron, while carbon has the most detrimental influence.

(2)   C. F. Burgess and James Aston of the University of Wisconsin thru grants from the Carnegie Institution of Washington have carried on for a number of years researches on iron alloys, using electrolytically refined iron of a purity of 99.97% iron as the basis. These researches have been published chiefly in the Electro-chemical and Metallurgical Industry for 1909 and Metallurgical and Chemical Engineering for 1910 * and partly in the Transactions of the Americal Electro-Chemical Society for 1909 and 1910.

The investigations cover alloys of copper, arsenic, tin, bismuth, antimony, manganese, nickel, silicon and various others. They probably form the most important series of researches upon the magnetic and electrical, as well as physical properties in general of iron alloys, as the purity of iron gives the assurance that the effect is caused by the allowing metal and not by a combination of this metal with the impurities of the iron.

As far as magnetic qualities are concerned the only metals that prove to be of any special interest are arsenic,

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*   The name of the former was changed to the latter in 1910. As a matter of fact it is the same journal.

bismuth, silicon and tin. The permeability is increased slight-
ly with these metals over that of the electrolytic iron, for
small percentages of alloying metal. The hysteresis loss is
decreased in some case to less than one half, and the resist-
ance is materially increased over that of the electrolytic
iron. The best results are obtained with 3.86% arsenic, 2.06%
tin, 2.00% bismuth and 4.66% silicon.

As a summary of the results thus far obtained by
different investigators is given in Table II the permeability
for H = 20 c.g.s. units.

3.   Theory and Method.

From the above table it is seen that all the elements
used to improve the magnetic permeability of iron are strong
deoxidizing agents, especially aluminium and silicon, whose
oxides are among the most stable known to chemistry. Again,
very small quantities of these elements have to be added to
produce the beneficial results; if more is added, the per-
meability is decreased.

These facts seem to point to the probability that
the function of these elements is to completely deoxidize the
iron, and the more pure iron there is in the resulting alloy
the better. On this assumption, if chemically pure iron could
be obtained and melted down without being contaminated by
oxygen or other elements, this would be the ideal iron for
magnetic purposes. As this is practically impossible, at
present at least, the best that can be done is to use as pure
iron as possible and employ as deoxidizing agent elements that,

TABLE II

Summary of Tests on Magnetic Properties of

Iron Alloys by Various Invesitgators.

	Investigators.	Alloy.	
1.	Barrett, Brown & Hadfield	2 1/4% Al. for H=20 B =	17000
2.	Burgess and Aston	3.86% As.	16300
3.	" " "	2.00% Bi.	16100
4.	" " "	3.56% As.	16100
5.	Sankey's Lohy's Sheet		16100
6.	Electrolytic Iron Forged		15900
7.	Burgess and Aston	4.14% As. 4.66% Si.	15900
8.	Hadfields Magn. Steel		15900
9.	Barretts pure Iron		15900
10.	Burgess and Aston	1.81% As.	15750
11.	" " "	.29% As.	15550
12.	Allens C. I.		15050
13.	Barrett, Brown & Hadfield	2 1/2% Si.	15000
14.	High Grade Sheet		14800
15.	Transformer Iron + 5% As.		14750

when oxidized, will form a slag on the top of the iron and
not be dissolved by it. This is known to be true of silicon
and alumina.

However, the analysis of the alloys prepared by
Prof. Burgess show that the amount of element added to the
iron before melting is practically equal to the amount of ele-
ment in the resulting alloy, which seems to indicate that
none of it is oxidized,unless the oxide is dissolved in
the iron. According to the present knowledge of the action of
these oxides, they do form a slag on the top of the iron and
are not dissolved. Consequently the conclusion may be drawn
that, while these agents may protect the iron from being oxi-
dized and deoxidize it if necessary, their main function in
improving the magnetic quality of the iron must be sought in
the alloys which they form with the iron. That elements which
by themselves are non-magnetic should be able to improve the
magnetic quality of a strongly magnetic element like iron does
not seem impossible after the discovery of alloys like the
Heusler alloys,composed of the three apparantly non-magnetic
elements: copper, manganese and aluminium. If in the first
place the saturation value of an iron alloy is higher than
that for pure iron it is evident that either the number of
elementary magnets or the magnetic moment of each of these, or
both, have been increased, since

$$B_s = K \times N \times m$$

where

B_s = saturation value

K = constant

N = number of elementary magnets for unit vol.

m = magnetic moment of each elementary magnet.

If, in the second place, the saturation value is constant, but the permeability has been increased below saturation, this shows that the mobility only of the elementary magnets has been increased.

The first change involves an atomic or ionic change in the material, while the second change involves more of a molecular change in the structure of the iron. For practical purposes the saturation value is of little importance if the permeability is high below saturation. Consequently, if an iron is obtained with fairly high saturation value and the mobility of the elementary magnets can be improved the solution of the problem will have been approached. The saturation value of pure iron is very high, it can probably not be increased, so that the problem consists in alloying pure iron with some element that will bring about this mobility. Boron has been shown to have a marked beneficial effect upon the conductivity of cast copper, and it has been suggested that it might have a beneficial effect also upon the magnetic quality of iron.

The experiments, therefore, consist in producing as pure iron as possible, by electrolytic deposition, melting this down with certain percentages of boron, forging the resulting ingots into rods and test their magnetic, electrical and mechanical properties.

II   MATERIAL   AND   APPARATUS

1.   Electrolytic Iron.

The composition of the electrolyte employed for the preparation of electrolytic iron is due to Prof. Burgess and is made up as follows:

Electrolyte per liter: 400 grams of ferrous suphate
crystals
50 grams of ammonium chloride

Anodes: These consist of 3/8" or 1/2" wrought iron plates placed far enough apart to allow about 2 inches between the anode and the cathode. Swedish charcoal iron has been used altogether, of the following composition:

Silicon	.032 %
Sulphur	.0002%
Phosphorus	None
Marganese	None
Carbon	.259%
Iron (by diff)	99.71%

Cathodes: As it was desirable to refine the iron twice, lead cathodes 1/16" thick,were employed in the first set of tanks and after these had been covered by iron about 1/4" thick, they were used as anodes in the second set of tanks.   As cathodes in these latter tanks were used Swedish wrought iron plates 1/16" thick. The deposited iron was stripped off of these plates without trouble.

Current Density: This was kept at about 5 amperes per square foot of surface.

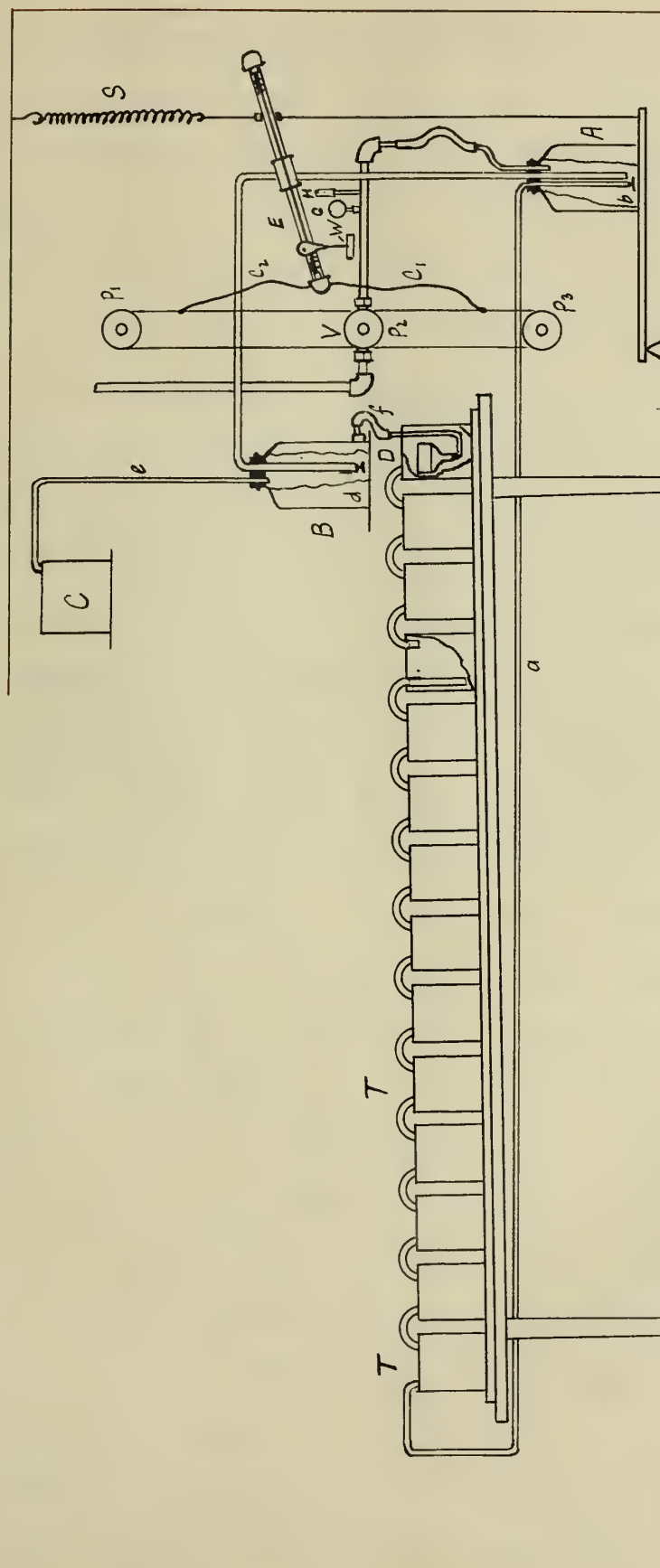Circulation of the Electrolyte: In order to insure a uniform

Fig. 3. Electrolytic refining plant.

composition of the electrolyte in all the tanks a slow circula-
tion was maintained all the time by the system shown diagram-
matically in Fig. 3. The electrolyte is syphoned from the
last tank T, into the receiver A. As the bottle fills up its
weight extends the spring, S, until the lever, E, attached to
it, gets into such a position that the weight, W, rolls by
gravity from left to right. This operation extends the spring
still further and opens the value, V, thru the cord, C, and
the pulleysystem p_1 , p_2 , p_3 .   The value V admits compressed
air into the receiver A, which closes the checkvalue "b" at the
end of tube "a" and forces the electrolyte up into the recevoir
B. The pressure is indicated on the gage ,G, and a safety
valve ,H, keeps the pressure within safe limits, about 10 pounds.
As the liquid is transferred from A to B the spring, S, contracts,
until W rolls back into its original position thereby closing
the valve thru the cord C_2. In the closed position the valve,
V, admits the air from A to the atmosphere. Another check-
valve, d, prevents the liquid from flowing back into A after
the removal of the pressure. An overflow tank, C, takes care
of any excess liquid thru the standpipe, e. The electrolyte
flows from B thru, f, into the filter-tank D, provided with an
upward filter, filled with fine quartz sand. From D, the
electrolyte flows by gravity thru the refining tanks by syphons,
as the table upon which they stand is provided with a slope of
three inches in 14 feet.

Fig. 4 is a photograph of the plant. It shows 12
refining tanks and one filter tank. The first six tanks are

Fig. 4. Electrolytic refining plant.

used for the primary refining and the next six for the second-
ary refining. The tanks are 8 1/2" by 10 1/2" by 12 1/2" high,
and each contains three anodes and two cathodes, the size of
each being 6" X 12", with an active surface of 6" X 9". The
anodes of one tank are connected to the cathodes of the next
tank thru triangular brass bars supported on wooden connect-
ing strips between the tanks.

As the water of the electrolyte is evaporated it is
replenished by destilled water and the density kept constant
at 1.16 by addition of more salt according to the formula
given. The anodes are removed and cleaned twice a week and
the cathodes three times a week.

The iron obtained was rather spongy and the deposi-
tion not very uniform. Its chemical composition showed by
analysis to be as follows:

	Single deposition	Double deposition
Silicon	.028%	.01%
Carbon	.083%	.01%

As the Swedish Iron Anodes contained only .0002% Sulphur, no
Phosphorus or Manganese, no analysis was made for these ele-
ments.

The doubly refined iron can therefore be taken as
between 99.97% and 99.98% pure.

2. Crucibles.

On account of the high melting point of pure iron,
about 1525° C, it was necessary to employ crucibles made from
fused magnesia, $M_g O$. A very pure grade of magnesite was

Fig.5. Electric arc furnace.

employed that had previously been calcined at 1000° C. This
material was placed in a specially designed electric arc
furnace shown in Fig. 5, holding about five pounds of material.
The inside chamber 4" X 4" X 6" is lined with 1/2" graphite
plates surrounded on all sides by 2" of calcined magnesite.
Outside this is placed firebrick laid on the flat side, so
that the total wall thickness is 7". The electrodes, consist-
ing of 2" graphite rods, enter thru holes in opposite sides
and slant slightly. It generally takes one hour to bring the
material to the fusion point.

The material thus obtained is ground down to 40 mesh
and mixed with hydrated magnesia $Mg (OH)_2$. The latter is pre-
pared by mixing 1000 grams of MgO with 600 c.c. of water and
allowing the mixture to react for 24 hours in a stone mill.
Just enough of this binder is used with the fused material to
make it moist enough to mould. The crucibles are formed in a
steel mould in a press capable of exerting a pressure of 4000
pounds. Twenty four hours are generally sufficient to dry the
crucibles, and they are then baked in an electric furnace at
1800° C for two hours. Covers are made from the same material
and in a similar manner. The size of these crucibles is 3 1/4"
high by 3" in diameter at the top, sufficiently large to hold
500 grams of crushed electrolytic iron. As magnesia becomes
soft at the temperatures needed for melting the iron, it is
necessary to place the magnesia crucibles inside graphite
crucibles. The latter, provided with covers, also help in
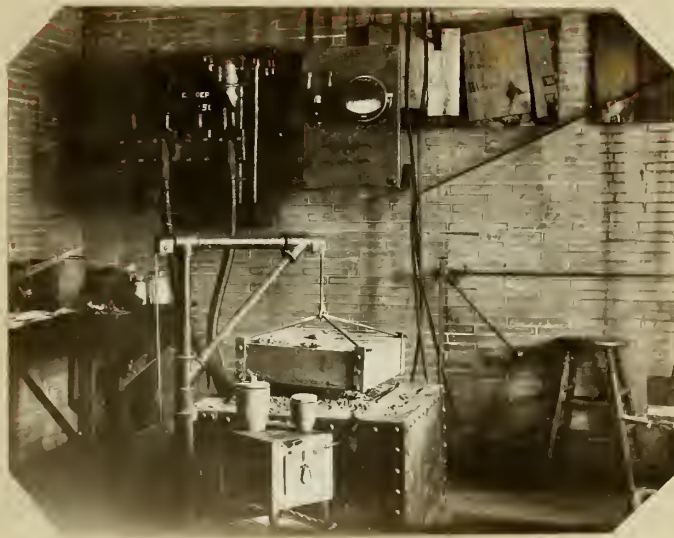keeping out impurities.

Fig. 6. Electric furnaces and crucibles.

3. Furnace.

The furnace used is a Hoskins 30 K.W. radiation
furnace, shown in Fig. 6. The current is sent thru graphite
plates, 30 on each side of the heating chamber, placed with
their flat sides against each other. On the back side the two
sets are connected by means of heavier plates and on the front
side each is connected to the source of energy thru round
graphite electrodes and water cooled terminals outside the
furnace. The current is delivered from the transformer at 25
volts, 60 cycles, so that at full load the furnace takes 1400
amperes. The current can be regulated by means of screws on
the back by either increasing or decreasing the pressure on
the plates. The maximum temperature of the furnace is 2000° C.

4. Alloying material.

As already mentioned, the alloying material used in
these experiments is a boron compound known as "Boron Suboxide."
It is manufactured by the General Electric Co. and used chiefly
in the production of copper castings. It has been described in
detail in papers by Dr. E. Weintraub before the American Electro-
Chemical Society in 1909 and 1910[*] where he gives its composi-
tion as $B_{15} O_2$ or $B_7 O$. It does not alloy with copper, but has
a great affinity for oxygen, as little as 1/30% of the material
freeing copper castings from blowholes.

5. Permeameter.

For testing the permeability of the alloys produced

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[*]   Trans. Am. Electro-chemical Society Vol. XVI page 165

"   "   "   "   "   Vol. XVIII " 207
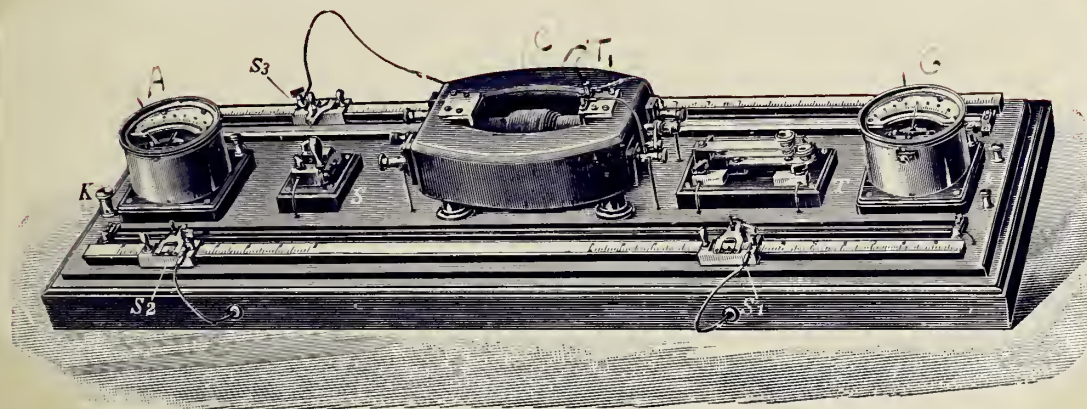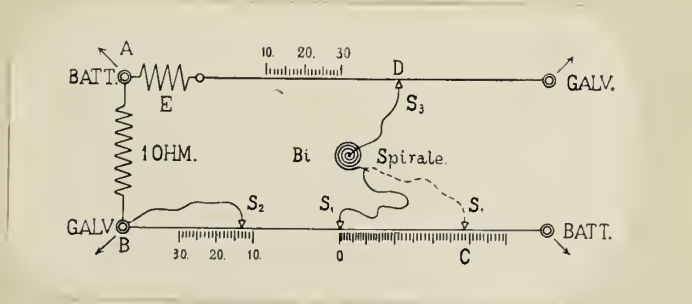
Fig. 7.

Fig. 8.

Permeameter & Connections.

a_1

; tc

, à
inctr

a Hartmann and Braun permeameter has been used. It is shown
in the cut of Fig. 7. It is essentially of the yoke type and
based on property of bismuth to vary its electrical resistance
the
with the magnetic field in which it is placed. A small spiral
made from Bismuth, .036 **cm. in** thickness is placed at the end
of a brass tube and inserted into the magnetizing coil, C, in
such a way that the spiral will occupy a position in the center
of the coil. The ends of the spiral are connected by copper
wire to the terminals T_1. The iron to be tested is turned in-
to two rods as shown in Fig.17 , .99 **cm. in** diameter and about
15 **cm.** long, and one rod inserted from each end so that their
ends fit closely up against the bismuth spiral. The method
consists then essentially in measuring the resistance of the
spiral with different magnetizing forces by means of a bridge
arrangement as shown in Fig. 8. The apparatus is self-con-
tained, the ammeter A shows the magnetomotive force H, and the
scale S_1 shows the induction B, when the galvanometer G gives
zero deflection upon closing the key T. On account of the
variation of the resistance of the spiral with the temperature
this variation must be compensated for before inserting the
test pieces, by placing the key S_2 on the existing temperature,
and while keeping S_1 on zero, moving S_3 until balance is obtain-
ed. This adjustment must be made at intervals during the test
as the spiral is liable to warm up or cool down.
Calibration of the permeameter.

As the scales of the instrument read the total mag-
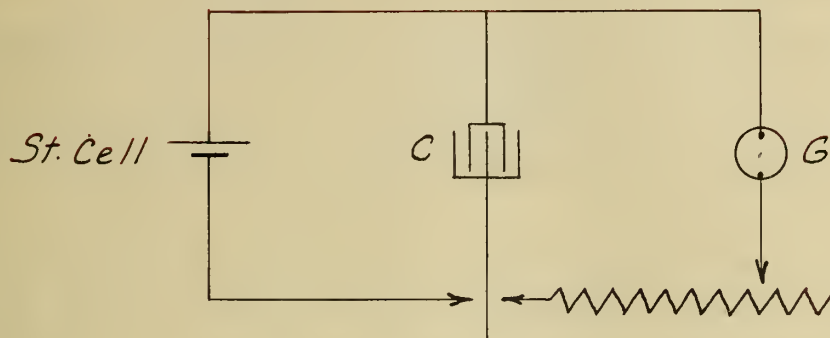netomotive force, H, for the complete circuit, including the

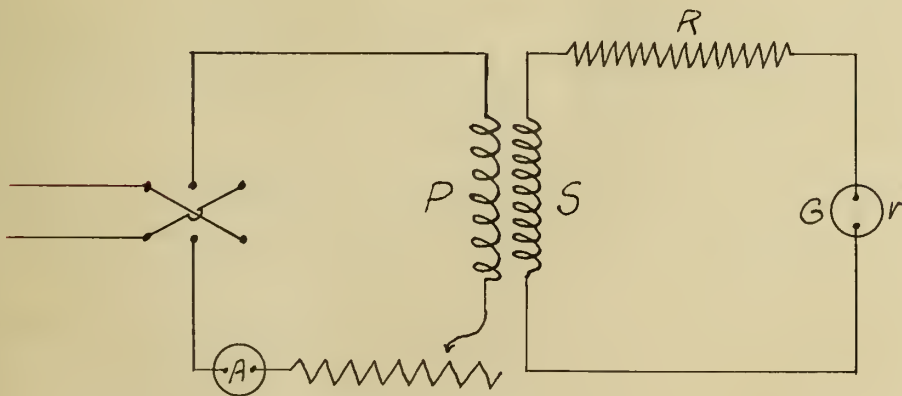Fig. 9. Connections for Galvanometer Calibration.

Fig. 10. Connections for Permeameter Calibration.

air gap, it was necessary to calibrate it in order to be able
to obtain the **true** B - H relation for the iron rods alone.

      For this urpose one long rod 30 cm. long and two
standard rods 15 cm. long were cut from the same plate of Swedish
charcoal iron. The tube Bismuth with the spiral was removed and another
tube made that extended clear thru the magnetizing coil. Upon
this tube was wound 251 turns of #32 wire and the ends brought
out to the terminals T_1. The long rod was inserted and the
induction measured by means of a Leeds and Northrup ballistic galva-
nometer, calibrated by standard cell and condenser.

      The connections for the calibration of the galvanometer
are shown in Fig. 9.

      Voltage of cell = 1.422 volts

      Capacity of condenser = 1/3 m.f.

      Deflection of Galvanometer = 75.0 small divisions

      Quantity discharged thru Galvanometer = 1.422 x 1/3 x
$$10^{-6} = .475 \times 10^{-6} \text{ coulombs.}$$

      Quantity per unit deflection = .00632 x 10^{-6} coulombs

      The connections for the permeameter calibration are
shown in Fig. 10.

    For the secondary circuit, if

      e_s = induced e.m.f. in secondary coil

      i = current flowing

      R, r, & S = resistances of rheostat, galvanometer
and coil.

We have:

$$e_s + i\,(R + r + S) = 0 \qquad\qquad (1)$$

$$e_s = - N_s \frac{d\varphi}{dt} \times 10^{-8} = - i (R + r + S) \quad (2)$$

Hence

$$d\varphi = \frac{r + R + S}{N_s} \, i \, d t \times 10^8$$

Integrating:

$$\varphi = \frac{r + R + S}{N_s} \, q \times 10^8 \quad (3)$$

where

q = total quantity discharged thru the circuit

If D = deflection of galvanometer due to a quantity q

$$q = .00632 \, D \times 10^{-6}$$

R = 100,000 ohms,   r = 3430 ohms,   S = 90 ohms

Therefore

R + r + S = 103520 ohms

N_s = 251

Substituting in (3)

$$\varphi = 41250 \times .00632 \, D = 260.5 \, D \quad (4)$$

Where φ = total change of flux in the magnetic circuit.   The area of the rod = .78 sq. cm. The magnetomotive force was calculated and found to be 50 x current in amperes.

The B - H curve was then obtained by the method of opening the circuit, reversing it, again opening it and again reversing it, reading the deflection every time.

Example:--

Corrected Current	H	change	Deflection	From (4) φ	φ_{max}	Av. φ_{max}	Av. φ_{res}	B_{max}	B_{res}
		1 - 2	6.8	1780	4170				
.041	2.05	2 - 3	25.2	6550		4225	2420	5400	3100
		3 - 4	6.7	1750	4280				
		4 - 1	26.0	6800					

$B \times 10^3$

18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

0 10 20 30 40 50 60 70 80 90 100 110 120

H

I

III

II

Fig. 11
Calibration Curves
for
Hartmann & Braun Permeameter.

I - Actual Saturation Curve by Galv. & Test Coil.

II - Saturation Curve for same Iron by Perme-
ameter.

III - Difference betw. I & II, representing an
Air-gap of .04 cm.
Swedish Charcoal Iron used.
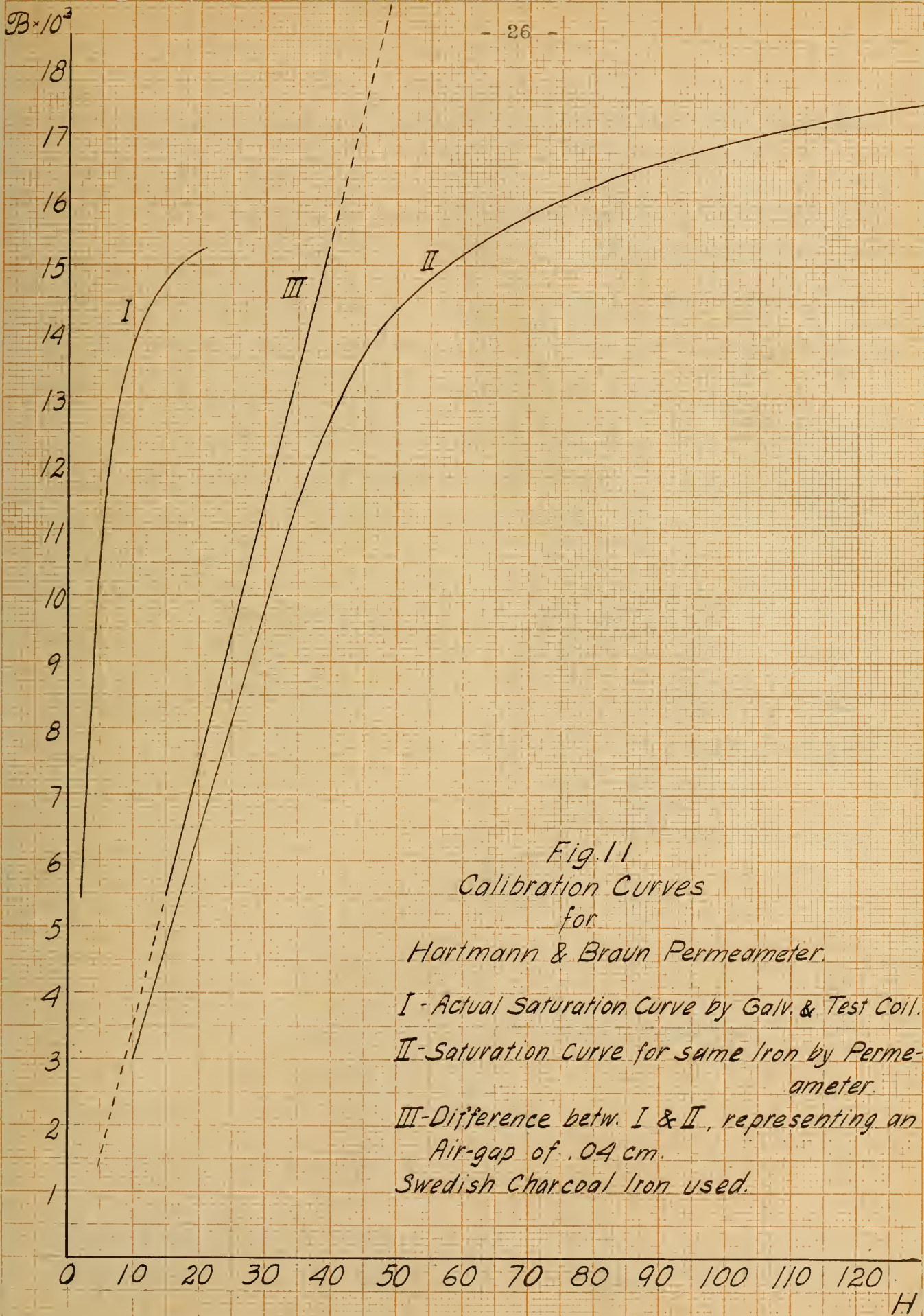
In this manner was obtained the true saturation curve as shown in Fig. 11.

The bismuth spiral was then replaced and the B - H curve obtained in the same way as above by using the test coil of 251 turns on the brass tube inserted into the magnetizing coil from the opposite end to the one containing the spiral. In this case the two standard specimen were used.

The curve thus obtained was found to coincide with the one obtained with the same test pieces by means of the bismuth spiral and permeameter scale. This curve is also plotted in Fig. 11.

The difference between these two curves is found to be practically a straight line. The equivalent airgap corresponding to this straight line is found in the following manner:

$$f_e \, l_e = f_a \, l_a + f_i \, l_i \quad (1) \text{ where "a" refers to airgap}$$

"e" equivalent

"i" refers to iron.

or since

$$f \, l = N \, I = \frac{10 \, H \, l}{4 \, \pi} \quad (2)$$

$$H_e \, l_e = H_a \, l_a + H_i \, l_i$$

or since

$$H_a = B \quad \text{and} \quad l_a \text{ practically equals } l_i$$

$$H_i = H - B \frac{l_a}{l_i} \quad (3)$$

or

$$l_a = \frac{l_i}{B} (H_e - H_i) \quad (4)$$

From Fig. 11 for $B = 6000$ $\quad H_e - H_i = 16.0$

Therefore, $\quad l = \frac{15}{6000} \times 16 = .04 \text{ cm.}$

that is the equivalent airgap of the magnetic circuit is .04 cm.
Even with this small airgap the inaccuracy of determining H
for small values of B makes the instrument practically useless
for obtaining the hysteresis loop. It must therefore be limit-
ed to the measurement of permeability.

5.   Annealing furnace:

The furnace used to anneal the alloys is shown in
Fig. 6, in front of the large furnace. It is a Hoskins 110
volts, 16 amperes 1000° C furnace, and was used successfully for
all the alloys except four pairs of rods. It broke down while
these were in the furnace, and they consequently had to be
annealed in a larger, radiation type furnace.

III THE PREPARATION AND
TESTING OF THE TEST PIECES

1. Cleaning the iron.

After removing the electrolytic iron from the re-
fining tanks it was thoroughly rinsed in boiling water to re-
move all of the salts adhering to it, and after drying, it was
stored away.

Due to the spongy condition in which the iron was
deposited, it left a very large surface exposed to the attack
of the air, and it rusted very badly. On this account it was
deemed necessary, as a precaution at least, to remove this
oxide previous to melting it. This was done as follows: 500
grams of the crushed iron was weighed out and placed in a
constantly stirred 1:3 hydrochloric acid bath until the iron
appeared bright all over. Boiled water was then introduced
into the vessel thru a glass tube that was used at the same
time to stir the iron.   After the bath became clear,
distilled water was introduced in a similar manner. Finally
the water was poured off and two baths of denatured alcohol
was applied. In most cases the required amount of alloying
metal was then added to the iron after pouring off the alcohol,
and the mixture at once placed in the crucibles ready for melt-
ing; but in some cases the iron was dried and left a day or two,
showing only small traces of rust. In two of the early melts,
3 B 05 and 3 B 06 this procedure was not followed, but iron was
selected that was rather free from oxide, and there seemed to

be little difference in the behaviour of the iron after melt-
ing. However, two melts were made from badly oxidized iron,
and in this case the ingots were so full of blowholes that
they were useless.

2.   Melting the alloy.

After placing the iron and alloying metal in the
magnesia crucible, the cover was cemented on by means of mag-
nesite, and the whole placed inside the graphite crucible and
covered by a graphite lid. Two pairs of crucibles were placed
in the furnace at a time. The current was started, brought up
to 110% normal value in about 5 minutes, and left at that value
for two hours, when it was reduced to normal load and left there
for another hour. By means of pyrometric measurements once for
all, this procedure would bring the temperature up to 1600° C
and leave it at that temperature until the current was shut off,
when it would decrease very slowly. After 18 hours the furnace
would still be too hot to allow the crucibles without asbestos
gloves.

No stirring of the molten metal was done, and it was
left to cool in the crucibles. In some cases the ingots could
be removed without trouble, but--in perhaps most cases--the
crucibles had sagged a little or altered their shape, so that
they would have to be broken to pieces.

The ingots were in nearly all cases satisfactory,
only in rare cases did blowholes appear, and in these cases
this may be attributed to too low a temperature in melting
down, giving the gases not sufficient time to escape.

3.   Forging the ingots into rods:

From the describption of the furnace it will have
been noted that the resistor consists of graphite plates. These
plates are naturally the hottest part of the furnace and would
be in a good condition to burn, if any oxygen should be presant.
It was rather expected that these plates would take care of all
the oxygen present, leaving the atmosphere if not reducing, at
least neutral. The experience in forging the ingots and the
final results seem to indicate that the iron was slightly oxidiz-
ed.

At first a great deal of trouble was experienced in
forging. The ingots were reheated to forging heat in an ordinary
forge and forged under a steam hammer. But in spite of every
precaution in cleaning the ingot beforehand, removing surface
flaws, and gentle application of the hammer, most of the ingots
would crack to pieces. This was the case with remelted Swedish
charcoal iron as well as with the electrolytic iron alloys, and
it seemed to make no difference as to the percentage of the alloy-
ing metal. It was observed all this time that the iron was ex-
ceedingly soft when cold and worked easily in the lathe.   Con-
sequently it was tried to forge the ingots at a rather dull red
heat or between dull red and a bright red. The attempt proved
very successful, and very little trouble was had in forging the
remainder of the ingots. But the cost of the experiment was
rather high, for out of a total of 52 ingots, only 19 made their
final appearance as rods. The reason why the ingots should not
forge at a forging heat will be discussed later.

4.   Turning the rods.

The forged rods were from 15 to 18 inches long by 1/2 inch square. From these were made two test pieces as shown in Fig. 17 for the permeability test, each about 5 1/2 inches long by .98 cm. in diameter, and one test piece for the tensile test, 2 1/2 inches long by   5/16 inch diameter over the middle 1 1/2 inch, with 1/2 inch threaded ends. One unbroken test piece is also shown in Fig.17 . The remainder of the rods were reserved for metallographic work.

5.   Testing the rods unannealed.

These test pieces were first tested in the unannealed state. The permeability test was performed on the Hartmann and Brown Permeameter, the resistance test on a Thomson's Double Bridge, especially adapted to low resistance work, and the tensile tests on an Olson's 10000 pound testing machine, driven unifomely by an electric motor. This latter test involved measuring the ultimate tensile strength, and the yield point and breaking load if possible. After the removal of the test pieces from the machine the elongation between two previously made punch marks, and the reduction of area at the fracture were measured.

The results of these tests are shown in Section IV.

6.   Annealing.

After completing the tests of the rods unannealed, they were placed, four pairs at a time in the annealing furnace already described. In order to prevent oxidation a small amount

°C

Molten Iron, and Carbon in Solution.

Freezing begins.

Freezing begins.
Iron with 2.2% Carbon separates and is precipitated from solution.

Freezing begins
Graphite separates.

Freezing ends

2.2% Carbon

Austenite solution

Eutectic Alloy
(Iron with 4.3% Carbon)

Cementite (Fe C₃) is precitated.

Ferrite is precip.

.9% Carbon

Eutectoid (Iron with .9% Carbon) is decomposed into Ferrite & Cementite and is called Pearlite.
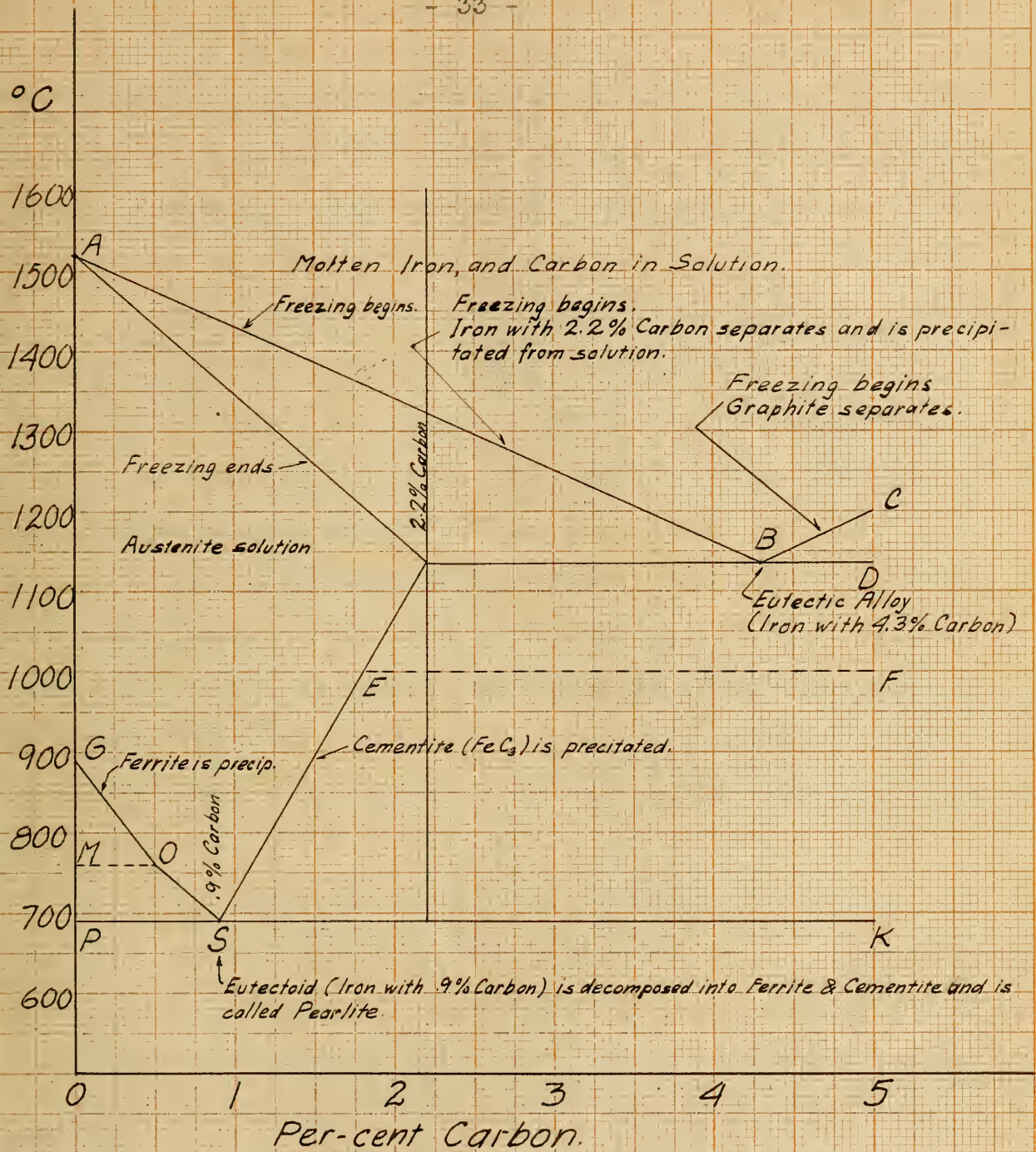
Per-cent Carbon.

Fig. 12. Complete Roberts-Austin-Roozeboom
Diagram for Iron and Carbon.

of illuminating gas was introduced together with the pyrometer thru the hole in the back of the furnace, and the hole plugged up with magnesite. Only enough gas was used to allow a small flame appearing at the front of the furnace.

The pyrometer used is a Heraeus Le Chatelier platinum ---platinum - 10% rhodium outfit, indicating the temperature directly in degrees centigrade. The thermocouple was placed in a tube of "Electroquartz" and the wires insulated from each other by means of a one-bore fire clay tube.

The normal current was turned on and the temperature rose uniformely to 900° C in about 50 min. The current was then regulated so as to keep the temperature at that point for 30 minutes, when the current was turned off and the furnace allowed to cool down slowly. The cooling was effected in about six hours.

The temperature selected for annealing, 900° C, was chosen from a consideration of the Roberts-Austin diagram for the transformation characteristics of iron and carbon. This diagram is reproduced in Fig. 12. A B C is the curve for beginning solidification, AaD that for completed solidification Between Aa and GOS the iron (ferrite) and the carbon are in solid solution and is called austenite. At the curve GOS ferrite begins to be precipitated until the solution contains ferrite with .9% carbon. Upon passing the point S, this final eutectoid is decomposed into ferrite and cementite and is called pearlite. Consequently an iron containing less than .9% of carbon will upon cooling contain ferrite and pearlite, the

amount of pearlite depending upon the amount of carbon; if
this is .9% all of the resulting mass will be pearlite.   As
the iron under consideration here contains only about .01%
carbon, no attention needs to be given to the part of the
diagram to the right of S.

Now, if the iron could be cooled suddenly from a
temperature above GOS, some of the solid solution would re-
main in the transition stages, martensite, troosite, osmondite,
or sorbite, all of which would tend to decrease the mobility
of the ferrite crystals. The sudden cooling would also tend
to prevent the transformation of gamma iron, (above 890° C)
and beta iron (above 760° C) into alpha iron (below 760° C).
The rate of cooling determines the degree of the transformation,
and the more complete it is the softer and more strongly magnetic
will be the iron. If iron that has been cooled too suddenly
for the transformation to take place, be reheated to above GOS
all of the previous crystalization will disappear, and upon
slow cooling the desired transformation may be obtained. For
nearly pure iron it is seen that GOS lies near 900° C, conse-
quencly such iron must be heated to about 900° C to effect the
desired result.

In spite of the precaution taken to prevent the rods
from oxidizing, they were coated with a thin layer of oxide
upon removal from the furnace. The thickness of this layer
was found to be about .005 cm., so that the reduction of di-
ameter amounted to about 1%, and the reduction of area to about
1.5%. This was corrected for in the final results.

IV RESULTS OF TESTS.

The method of marking the specimens is as follows:

Sw. I - 2 stands for Swedish charcoal iron not remelted, specimen No.2.

1 - 02 stands for Swedish charcoal iron remelted in electric furnace with no addition, specimen No. 2.

3 - 09 stands for doubly refined electrolytic iron melted without addition of any alloying metal, specimen No.9.

3 B 12 stands for doubly refined electrolytic iron melted with boron, specimen No. 12.

As the results will be recorded later in an Engineering Experiment Station bulletin, the tables for the B - H curves will not be reproduced here, except for two of the specimen to show the method.

The following is a list of the specimen tested:

Sw. I 3	Swedish iron not melted			
1 - 02	Swedish iron remelted with no addition			
3 - 09	Electrolytic iron with no addition			
3 B 23	"	"	"	.25% boron
3 B 05	"	"_	"	.5% "
3 B 24	"	"_	"	.75% "
3 B 06	"	"	"	1.0% "
3 B 26	"	"	"	1.5% "
3 B 13	"	"	"	2.0% "
3 B 14	"	"	"	3.0% "
3 B 18 + 3 B 22 "		"	"	4.0% "

TABLE III

Data for B - H Curve for

Sw. I - 3

Area unannealed = .773 sq. cm.

" annealed at 950° C = 765 sq. cm.

For annealed rods.

H_e (for complete magn. Circuit)	B'	B (corrected $=B' \times \frac{773}{765}$)	H_a (For air Gap)	H_i (For Iron)
10	3350	3390	10	0
20	6950	7040	19	1
30	10500	10630	27.7	2.3
40	13000	13170	34.0	6.0
50	14450	14630	37.6	12.4
59.	15130	15330	39.5	19.5
73.5	15960	16160	41.6	32.0
98	16720	16930	43.5	54.5
125.0	17300	17520	45.0	80.0
145	17700	17930	46.0	99.0
172	18100	18330	47.0	125.0
195	18430	18680	48.0	147.0
245	19100	19350	48.0	197.0

TABLE IV

Data for B - H Curve for

3 B 20 (8%)

(Tested with Sw. I. - 3 annealed)
(See Table III)

Area unannealed = .775 sq. cm.

" annealed at 900° C = .770 sq. cm.

For annealed rods.

H_e (For Compl. Magnetic Circuit)	B'	B ($=B' \times \frac{775}{770}$)	H_a (For Air Gap)	H'_i ($H_e - H_a$)	H''_i (For Sw. I. - 3.)	H_i ($2H'_i - H''_i$) for 2 B 20
20	6150	6200	17.0	3.0	.6	5.4
30	9250	9300	24.7	5.3	1.7	8.9
40	11560	11630	30.5	9.5	2.8	16.2
50	12900	13000	34.0	16.0	4.7	27.3
60	13850	13950	36.0	24.0	7.8	40.2
75.5	14900	15000	39.	36.5	14.6	58.4
96.	15780	15880	41.	55.0	25.0	85.0
125	16470	16580	43.	82.0	38.0	126.0
147.5	16900	17010	44.	103.5	53.0	154.0
170.	17300	17410	45.	125.0	70.	180.0
198.	17700	17810	46.	152.0	83.	221.0

TABLE V.

Mechanical Tests.

Specimen	%	Area sq.in.	Ultimate Strength lbs/sq.in.	Area. of Fract. sq.in.	Red. of Area. %	Elong %
Sw. I.		.0728	40000	.0314	57%	36.0
1 - 03	0%	.074	55000	.0095	87.0	42.0
3 - 08	"	.079	70600	.035	55.7	20.0
3 - 09	"	.0782	71300	.038	51.3	25.0
3 B 05	1/2	.073	49600	.038	48.0	30.0
3 B 24	3/4	.073	62600	.0255	65.0	32.0
3 B 06	1	.072	51200	.0227	68.5	33.0
3 B 26	1 1/2	.08	49100	.0255	68.0	43.0
3 B 13	2	.0685	56500	.0255	63.0	40.0
3 B 15	4	.0778	57300	.0347	55.5	26.0
3 B 16	5	.0728	63200	.0416	43.0	23.0
1 B 01	1	.073	57600	.0314	56.0	26.0
1 Si.01	2 1/2	.0782	74500	.0492	37.0	23.0
3 Al.02	2 1/2	.075	64400	.0705	6.0	10.0
3 Al.04	2 1/2	.077	96800	.072	6.5	12.0

TABLE VI

Resistance of Iron - Boron Alloys.

Specimen.	No. of Rods.	% Alloying Metal.	Resistance ohms/cm.^{3} x 10^{-3}
1 - 02	2	0	.0193
3 - 09	"	0	.0231
3 B 23	"	.25	.0192
3 B 05	"	.5	.0198
3 B 06	"	1.0	.0208
3 B 26	"	1.5	.0186
3 B 13	"	2.0	.0206
3 B 14	"	3.0	.0198
3 B 18	1	4.0	.0402
3 B 22	1	4.0	.0203
3 B 16	2	5.0	.0203
3 B 19	"	6.0	.0233
3 B 20	"	8.0	.0216
1 B 01	2	1.0	.020
1 Si. 01	"	2.5	.063
3 Al. 02	"	2.5	.0232
3 Al. 04	"	2.5	.0545

3 B 16   Electrolytic iron with   5.0%   carbon

3 B 19   "   "   "   6.0%   "

3 B 20   "   "   "   8.0%   "

Table III gives the data for the B - H curves for Sw. I. - 3 annealed at 950° C.

Table IV gives the same for 3 B 20, but in this case only one rod was obtained, and consequently it has to be tested together with a rod of different composition, but whose B - H curve was known.

Table V gives the results for the mechanical tests of unannealed rods.

Table VI gives the results for the resistance test of unannealed rods.

The results of the various tests have been plotted in figures 13 and 16 incl.

Fig. 13 gives the B - H curves for the various specimen unannealed and Fig. 14 gives the B - H curves after annealing at 900° C.

In Fig. 15 the values of H are plotted against the percentage of boron added to the various specimen. The upper curves in the sets are for unannealed rods, the lower for annealed rods.

Fig. 16 is a summary of the mechanical tests of unannealed specimen together with the magnetic characteristics for B = 12000 and unannealed rods. The top curve shows the variation of ultimate strength, the second the variation of the reduction of area, and the third the variation of elongation, all plotted against the percentage of boron added.
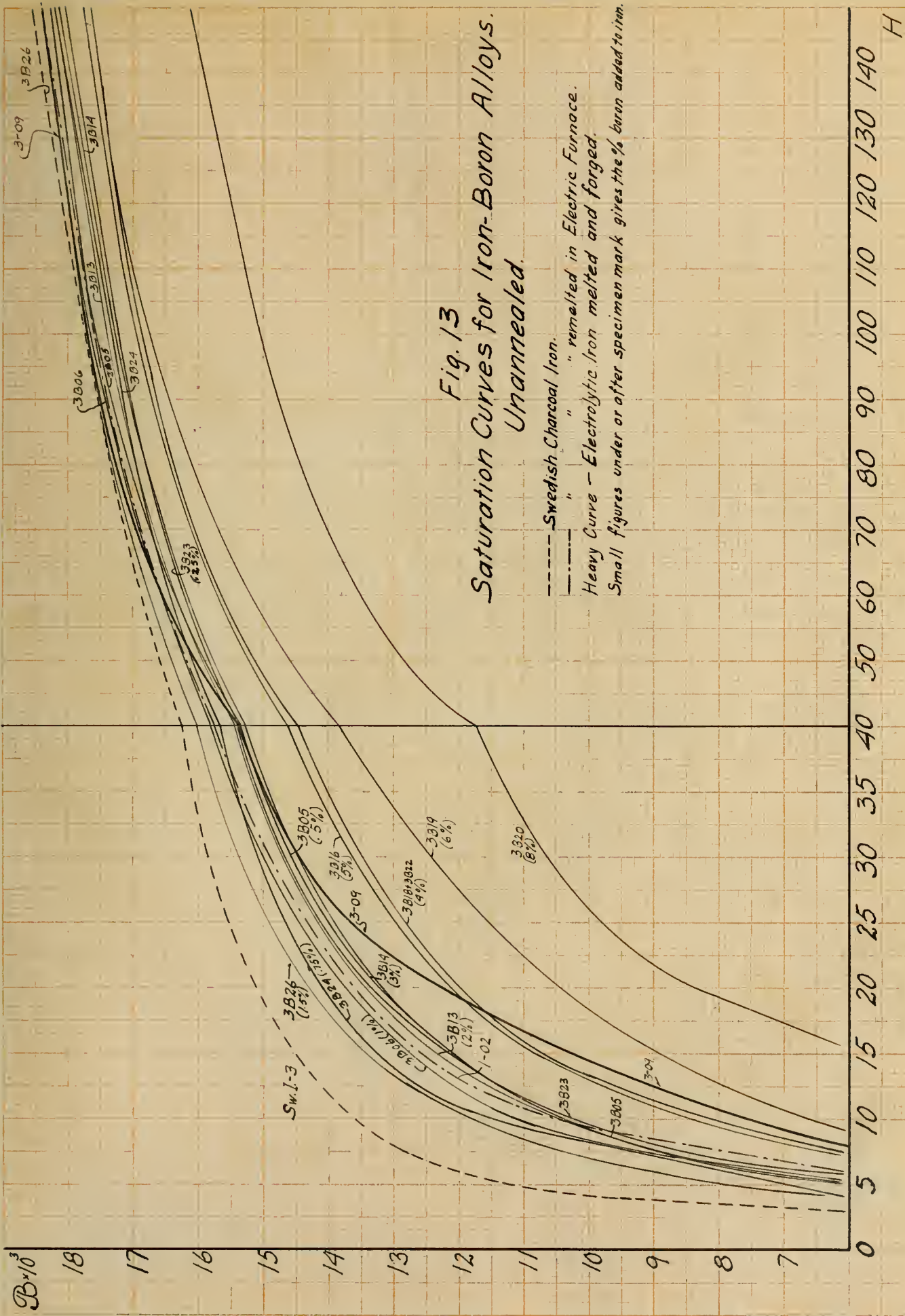
Fig. 13
Saturation Curves for Iron-Boron Alloys.
Unannealed.

Fig. 14.

Saturation Curves for Iron-Boron Alloys.
Annealed at 900°C.

—·—·— Swedish Charcoal Iron
——— " " remelted in Electric Furnace
——— Heavy Curve — Electrolytic Iron
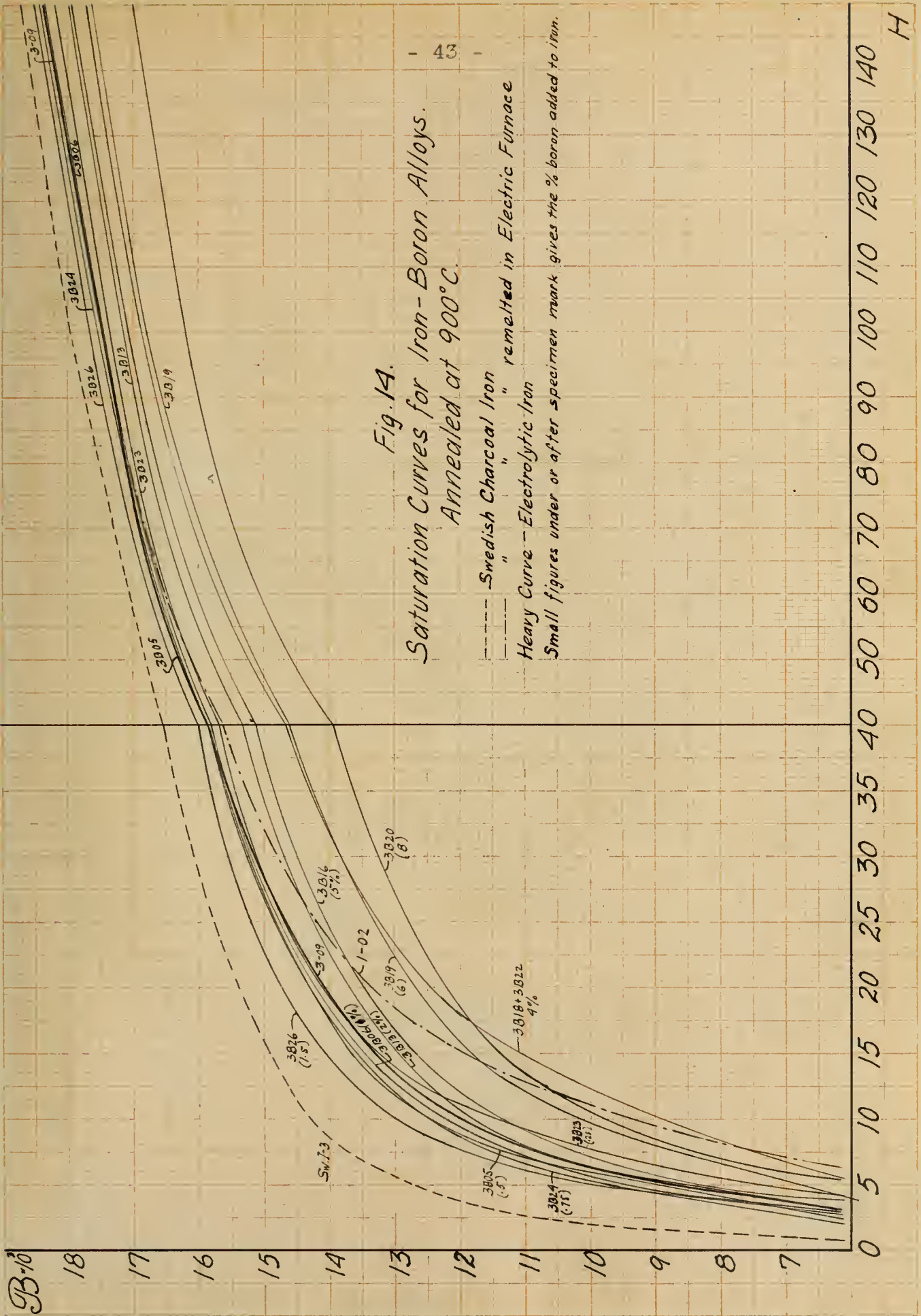Small figures under or after specimen mark gives the % boron added to iron.
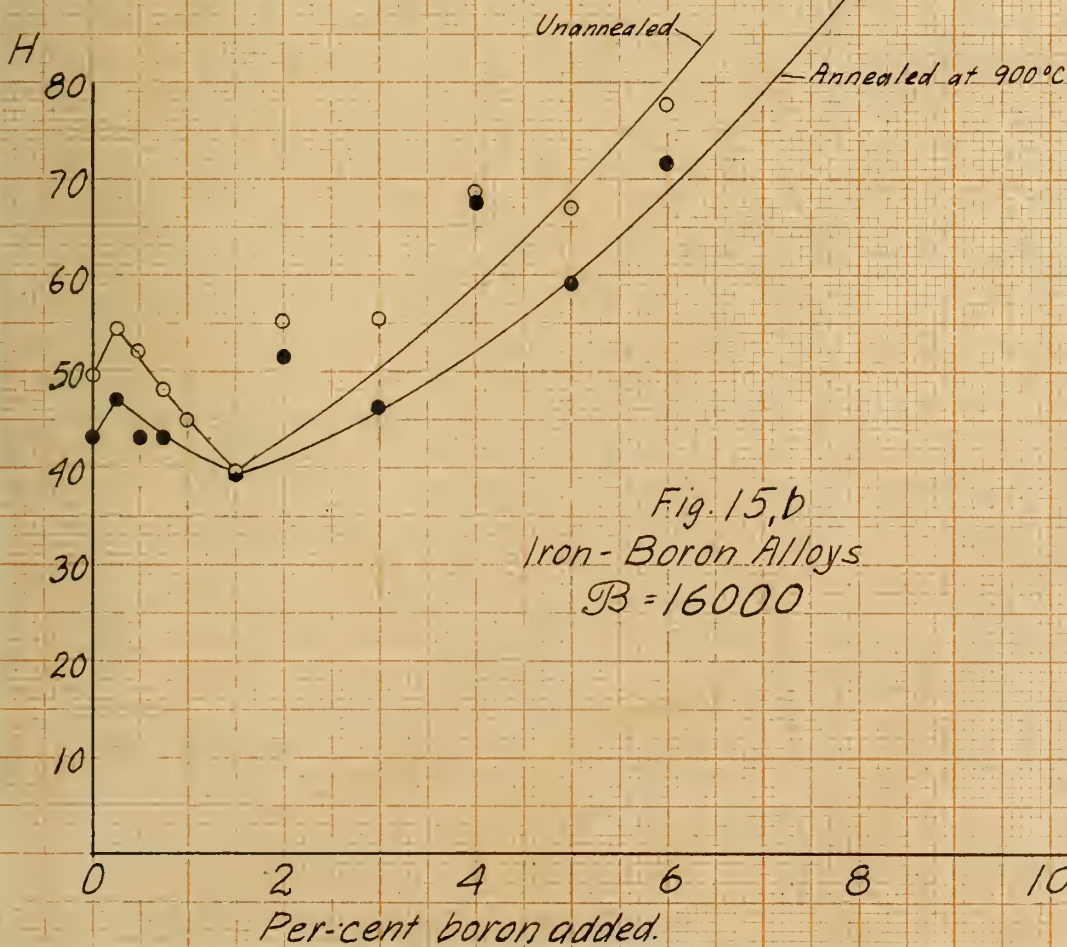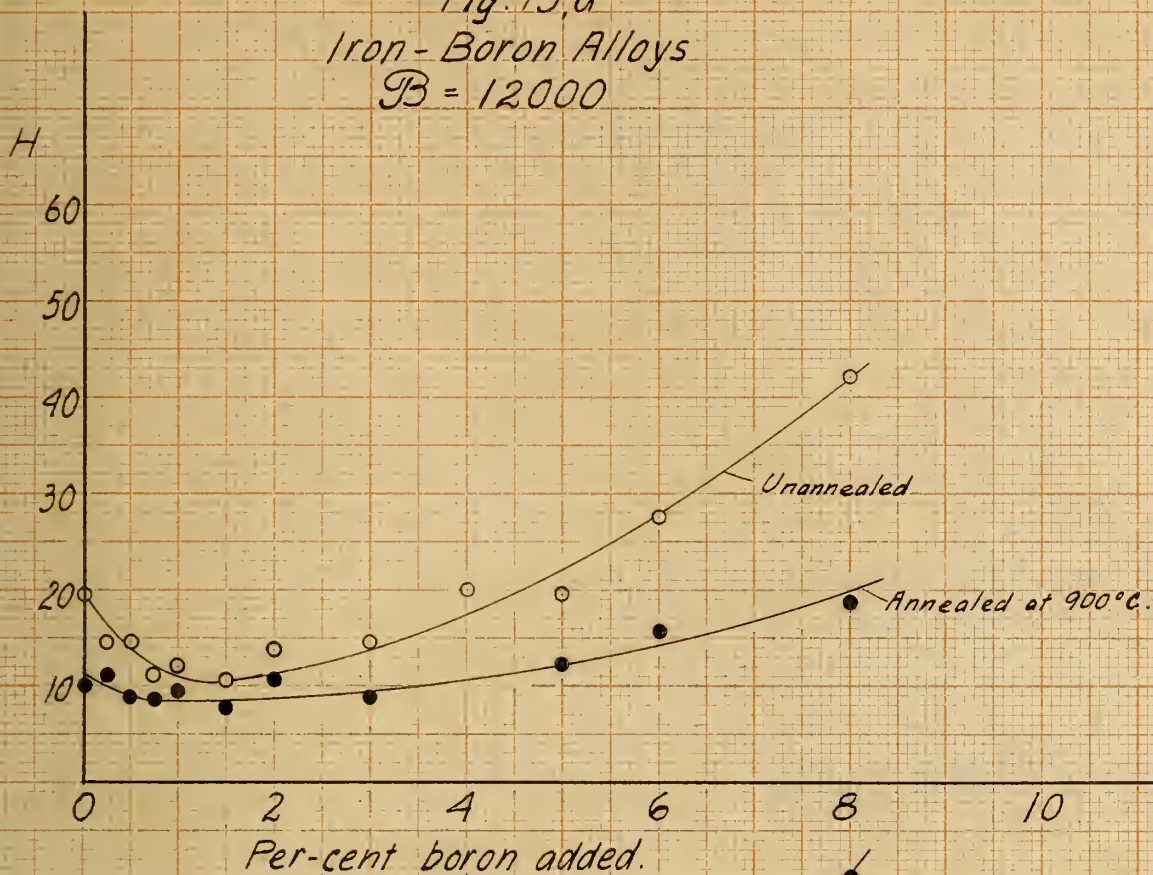
Fig. 15, a
Iron - Boron Alloys
$B = 12000$

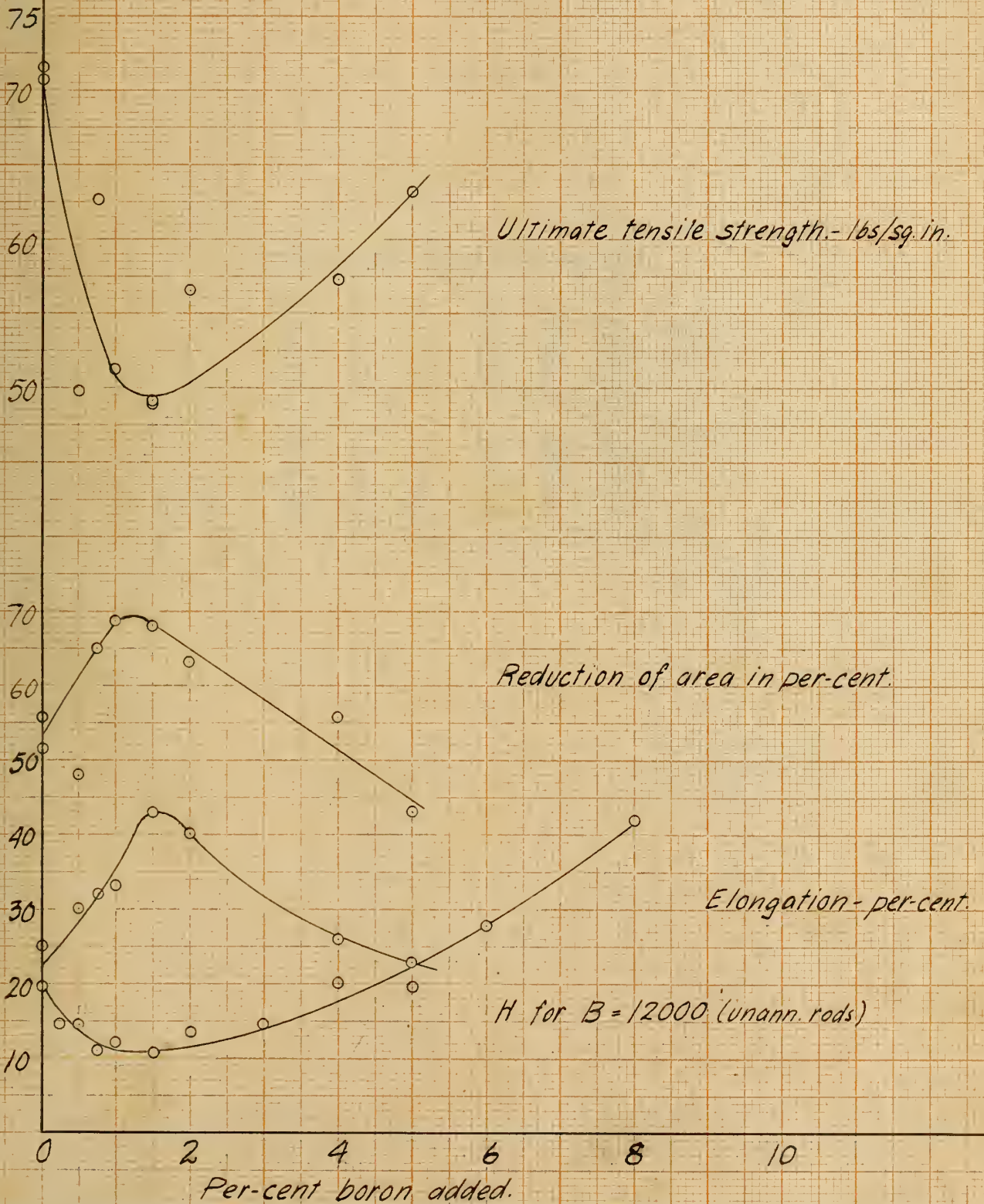Unannealed

Annealed at 900°C.

Per-cent boron added.

Fig. 15, b
Iron - Boron Alloys
$B = 16000$

Unannealed

Annealed at 900°C

Per-cent boron added.

Fig. 16.
Iron-Boron Alloys.

Ultimate tensile strength.- lbs/sq.in.

Reduction of area in per-cent.

Elongation- per-cent.

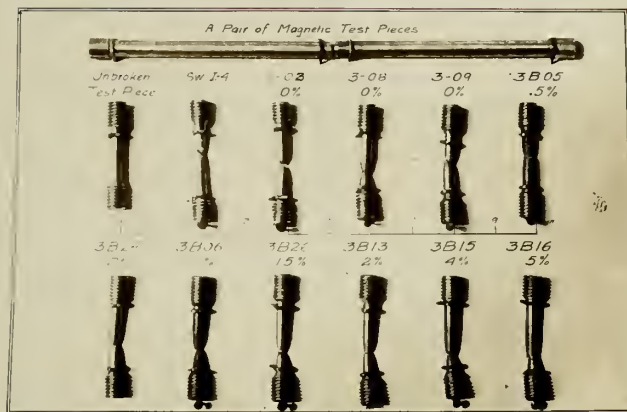H for B = 12000 (unann. rods)

Per-cent boron added.

Fig. 17. Tensile test pieces after being broken.

In Fig. 17 is exhibited the tensile test pieces after the mechanical test, together with a pair of the magnetic test pieces.

V SUMMARY AND CONCLUSION

An inspection of curves 13, 14, and 15 shows that
there is a marked improvement in the permeability as the addi-
tion of boron suboxide is increased from zero to 1 1/2 percent.
With further increase the permeability decreases, at first
slowly and then, after the four percent mark has been passed,
very rapidly. Fig. 15 shows an improvement in the permeability
for the annealed rods, especially for very low and very high
percentages of boron.

In Fig. 16 is shown very effectively the relation
between permeability and mechanical ductility. Just as the
permeability is a maximum for 1 1/2% of boron suboxide, so the
elongation and reduction of area at the fracture reach a max-
imum and the ultimate tensile strength reach a minimum for the
same alloy.

Further inspection of figures 13 and 14 reveals the
fact that the permeability of the Swedish charcoal iron has
been very materially reduced by melting in the electric furnace
without addition of any alloying metal. This fact together with
the previously mentioned difficulty experienced in forging the
ingots suggests strongly that the iron has been slightly oxidiz-
ed in the electric furnace. As this oxidation can readily be
avoided by surrounding the crucibles with charcoal or broken up
graphite plates it seems very likely that the permeability of
all the alloys will be raised materially. However, as far as
comparison is concerned, the fact remains that for similar
treatment the permeability is increased with small additions

of boron, and is higher for these alloys than for the Swedish charcoal iron.

The change in the slope of the B - H curves after annealing seems rather curious. Take, for instance, the curves for electrolytic iron without addition, 3 - 09, before annealing the curve is nearly straight at first and has a rather sudden bend, at H = 30, while after annealing the curve rounds off much more evenly with much higher permeability at low densities than for the unannealed rods. Just the opposite is the case with the remelted Swedish charcoal iron, and other alloys follow one or the other of these two, without any apparent connection with their composition.

The resistance tests do not bring out any marked difference one way or the other between the various alloys, except for 3 B 18, 4% boron, whose resistance is very high compared with the rest. 3 B 22 with the same percent boron does not show such high resistance, which seem to indicate that 3 B 18 is abnormal in some respect. For the B - H curve these two were tested together as only one rod was obtained for each. Fig. 15 shows that the points for these rods are far outside the average curves. The resistance test explains why this may be so, and justifies ignoring these points in drawing the curves.

That no increase takes place in the resistance is surprising in view of the results of Barrett, Brown and Hadfield, mentioned in the introduction, according to which 1% of one of the metals referred to increases the specific resistance of iron by an amount inversely proportional to the

atomic weight of the alloying metal.

According to their results 1% of Aluminium with an
atomic weight of 27 increases the specific resistance by 11.1%,
so that 1% of Boron whose atomic weight is only 11 should in-
crease the specific resistance by

$$\frac{27}{11} \times 11.1 \text{ or about } 27\%$$

As no increase in resistance takes place boron must be suppos-
ed to act like a nonmetal, like carbon for instance, in this
respect. In order to obtain an alloy that would be suitable
for magnetic purposes, then, it might be necessary to use an
alloying metal besides boron, for instance aluminium $\overset{or}{}$ silicon
to increase the resistance of the alloy, as this is desirable
in order to keep the eddycurrents as low as possible.

In conclusion the writer wishes to express his
appreciation to Dr.Grinnell Jones of the Chemistry Department
for assistance with the electrolytic refining plant, to Mr.
Justa Lindgren for the close attention given to the chemical
analysis of the iron, to Mr. A. T. Lanham of the forge shop
for assistance with the forging of the ingots, and to Prof.
H. F. Moore of the Theoretical and Applied Mechanics Department
for assistance with the mechanical tests.

VI   APPENDIX

On pages 91 - 93 of his book on "Composition and
Heat Treatment of Steel" Mr. E. F. Lake, Steel Editor of the
American Machinist, treats of boron and its influence upon
iron and steel. On page 92 he says: "Boron may be said to
give steel a hardness that increases its strength, up to a
content of 2% of boron, provided the carbon is kept below .02%,
but beyond a content of 2% boron or 0.2% of carbon the metal
becomes so brittle that it is weakened and easily powdered
under the hammer."

The mechanical tests recorded in this thesis do not
seem to verify this statement. With a carbon content of .01%
the ultimate strength decreased with increase of boron up to
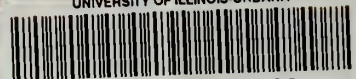1 1/2% while the ductility decreased.

In order to test the influence of boron upon iron
of higher carbon contents, specimens were prepared using Swedish
charcoal iron and 1% boron. This alloy has a B - H curve that
almost coincides with that for 3 B 19, containing 6% boron,
and the mechanical tests, (See Table V) show a slight increase
in strength and hardness over the same iron to which no boron
had been added.

While no general conclusion can be drawn from this
one sample, it seems as tho boron may have a beneficial in-
fluence upon the magnetic qualities of iron of low carbon con-
tent, while its influence upon iron of .2% carbon or above may
be detrimental.